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MODELING OF PREVENTIVE NITROGEN INERTIZATION IN UNDERGROUND MINES

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ABSTRACT Paper presents feature methods for merözatıon of a long coal face with retreat mining and method for computer modebng of this process The modeling is based on convection diffusion transfer Due to necessity of evaluation of more than one impurity into air-gas mixture, solution is obtained via consecutive diffusion mixing The method is appropriate when transport medium and impurity consist same physical and chemical components Computer program is also developed It reflects main tactical requirements for reduction of explosivity nsk when closing fire sectors

1 INTRODUCTION

Explosions of flammable gases, especially when they initiate dust explosions have caused more fatalities than any other type of mine disasters One effective way to lessen explosion hazard while fighting mine fires is reduction of oxygen content in air in the nsk zone via inert gas or exhaust gas- water vapor mixture injection into incoming air flow

Nitrogen has been regularly used for anti-fire ınertızation in underground mines for more than 18 years In the last decade this gas has prevailed as the basic mert agent m SPONCOM and open mine fires fighting Preventive nitrogen injection has nowadays become a regular means to suppress SPONCOM development as a result of mertisation technology progress

Nıtıogcn application for SPONCOM fire fighting in Bulgaria was initiated in 1983 in the biggest underground coal mine on the Balkan Peninsula - Babino mine Sub-bituminous coal is mined there from two seams The cual has the highest laboratory proven proncness (Markov 1089) to si>ON(_OM and practi (.ally established (Michaylov, 1987) fire hazard in Unljwna This mine is also classified as over-category ku ii thane emissions Figure 1 shows mcrtization laici for January 1994 to February 1996 period when torn moüuıUiM. i! tumpiexes were at work Monthly nitrogen consumption in Babino mine vanes from 1 108 10fl to 2 165 500 NmVmo showing average values for t ht period 1 108 300 NmVmo Overall expenses loi both target and volumetric incru/ation an trimeiidous (figure 1) taking into aaounl fiiaf wist of INm' gaseous nitrogen is approximately the , me as the price of İ kWh eleeh ıcıly

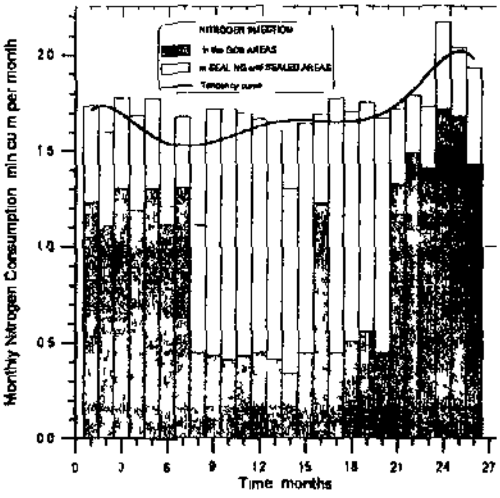


Figure 1 Nitrogen Injection vsTime

The basis for all modern engineering approaches foi reduction of explosion ri'k timing mint, fires fighting is set ou! in the remaikabie icscaieh woik (/itbetakis 1961) Definitions implied thcie for evaluation of boundary points showing explosion zone oi dir gas mixtures an also used in oui lesearch

Great increase ot nıtıogcn consumption in target and volumetric tnei ligation it^uires an engineering ground toi the necessaiy nitrogen volumes bom technua! and tattic<ii point of view I lie paper picsents possibilities for dynamic modeling of Urgit ,uul volumetric nuili/alion processes m toal panel with utiuit nimmt "'" 'dum Ü vtrililation schuni

2. FEATURE INERTIZATION CASES

Target and volumetric inertization can be applied in feature cases shown on Figure 2 for either keeping normal or reduced ventilation of inerted zone. Target and volumetric inertization as well as SPONCOM or open fires inertization differs significantly in tactic parameters of application - place of injection, volume to be inerted, necessary nitrogen volume and permissible amounts of nitrogen.

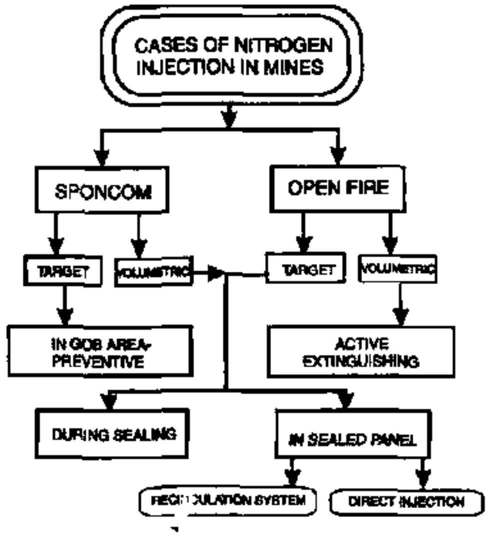


Figure 2 Feature Inertization Cases

Open or SPONCOM fires in retreat long faces (Fig 3) can occur in any place within the panel as well as in gob (branch 5-6)

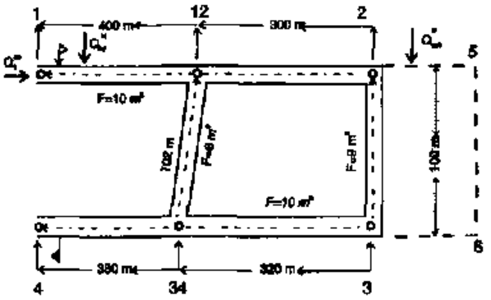


Figure 3 Fires in Retreat Long Faces

Place of fire occurrence predefines appropriate localjon for nitrogen injection They are summarized in Table 1 In third and fourth columns cases are described when at the moment of open fire occurrence nitrogen has been injected into the gob (branch 2-5). In the last column target inertization of SPONCOM fire in gob is specified.

Table 1 Fire and Nitrogen Injection

Place of Fire	Nitrogen Injection in branch				
	1-12	12-2	1-12& 2-5	12-2& 2-5	2-5
1-12	A1	-	-	-	-
12-2	A2	A3	-	B2	-
12-34	A4	-	-	-	-
2-3	A5	A6	B1	B3	-
3-34	-	A7	-	B4	-
34-4	A8	-	-	B5	-
5-6	-	-	-	B6	C1

3. TACTICS AND TACTICAL RESTRICTIONS OF INERTIZATION

From tactical point of view the most dangerous in regard to gas explosion are the fires at the coal face (branches 2-3 and 3-34). Inertization process modeling should allow simulation and study (in aspect of forecasting) of any of the cases described in Table 1.

For target inertization of gob area (C1 in Table 1) for suppression of SPONCOM development (fiction" branch 5-6 on figure 3), maximal nitrogen volume QCx> $^{t0 \quad De}$ injected into branch 2-5 is limited by safety standards for minimal oxygen content [0 l in panel access workings and is given by expression

$$Q^{gob}_{max} \le Q^{air}_{2} \frac{\frac{[O_2]^{min}_{3-4}}{[O_2]_1} - \left(1 + 0.01[CH_4]^{max}_{3-4}\right)}{1 - 0.01[O_2]^{N}_{inj}} \quad |m^3/min| \qquad (1)$$

In medial brackets volume concentrations percentages of corresponding gases are given while index shows branch number according to Figure 3 Technical nitrogen purity described by oxygen content $[O_2]^N_{inj}$ in it varies in the range 1 * 3%vol Expression (1) is used in modeling.for upper limit evaluation of admissible nitrogen volume as by oxygen factoi

Our observations on practical inertization of gob area (Cl), show that when injection point (for instance point 5 on Figure 3) is al a distance less than 25 m from caving line (point 2), preventive injection requires 2 to 6 times less nitrogen volume than evaluated by (1) When serious risk of transfer of SPONCOM into open fire exists eventually leading to explosion into the gob, then the value calculated by (1) is reached-

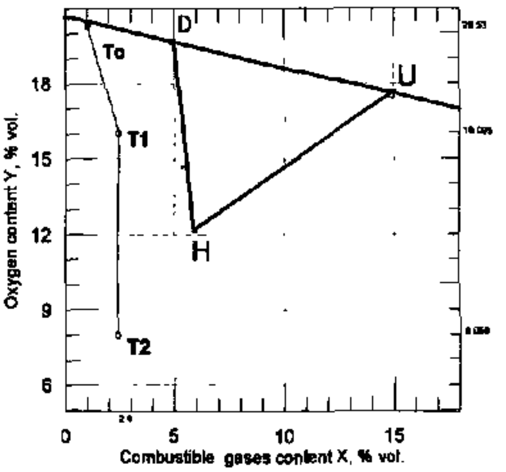


Figure 4 Explosibilily Triangle

Volumetric mertization tactics for explosion prevention during sealing of fire districts is illustrated with point T in the field of explosively diagram (Figure 4) It passes through the following three stages:

A) Air quantity decrease in fire region via building of anti-fire walls with ventilation windows in intake and return flows. Moreover flammable gases (X) and oxygen (Y) concentrations point $T_0(x_0, y_0)$ presenting initial conditions of ventilation, moves after droseling of ventilation flow from Q *" to Q "'r in $T_1(x_1, y_1)$. Its coordinates are.

$$x_1 = \frac{x_D}{k} \quad [\% \text{ vol.}]$$

$$y_1 = \left(1 - \frac{\frac{x_D}{k} - x_0}{100 - x_0}\right) y_0 \quad [\% \text{ vol}] \qquad (2a)$$

where:

x_D - lower explosion limit of air-gas mixture, defined in taking into account all flammable gases according to Le Chateiier [4],

k - dimensionless safety coefficient reflecting rate $\left(k = \frac{x_D}{x_1}\right)$ of flammable gases concentrations approaching their lower explosion limit x_D

k can take values in the range 1.7 to 2 due to explosion safety considerations This narrow scope of k variation reflects technically reasonable compromise between wish for high degree safety *(k>2)* and easier injection of small nitrogen volumes *(k* <1.7).

Using symbols, corresponding to that on figure 4, air quantity needed for evaluation of hatches in fire stoppings can be defined:

$$Q_1^{air} = \frac{\left(x_0 - [CH_4]^{air}\right) Q_0^{air} - \frac{x_D}{k} Q_{gob}^N}{\frac{x_D}{k} - [CH_4]^{air}} \quad [m^3/min]$$

(2)

When nitrogen is not injected in gob$(Q_{gob}^N = 0)$ and methane content in incoming airflow İs negligible $([CH_4]^{air} \approx 0)$ from (2) can be obtained:

$$Q_1^{air} = k \frac{x_0}{x_D} Q_0^{air} \quad [m^3/min] \qquad (2b)$$

B) Injection of nitrogen of v o l u Q_2^N s o as air-gas mixture can be moved along line $\overline{T_1T_2}$ to point T_2 with coordinates:

$$x_2 \equiv x_1 \qquad y_2 < y_H \qquad (3a)$$

via substitution of part of air volume with nitrogen as follows:

$$Q_2^{air} = Q_1^{air} - Q_2^N \quad [m^3/min] \qquad (3)$$

In expression (3) y^ is oxygen coordinate of ignition peak (point İ on figure 4) defined under Le Chateiier rule, white low indices correspond to point T location on the same figure

Choice making of y_2 depends on nitrogen volume

$$Q_2^N = \frac{\left([O_2]^{air} - y_2\right) Q_1^{air} - \left(y_2 - [O_2]^{N}\right) Q_{gob}^N - y_2 Q_{CH_4}}{[O_2]^{air} - [O_2]^{N}} \quad [m^3/min] \qquad (4)$$

which can be injected under the substitution condition (3).

C) Closure of hatches m fire stoppings of intake (branch 1-12 or 12-24 of figure 3) and return (branch 34-4 or 2-34) flows, which accordi-g lo valid requirements in most of safety rules, should be done simultaneously. As a result air volume which pass through fire district is reduced from *Q'''* to air leakage *Q''* through stoppings. Further inertisation depends on isolation tightness, pressure on stoppings and rate of methane release Q_{CH} in sealed volume.

Our opinion is that safe compacting of stoppings can be undertaken only when oxygen concentration reaches value of $x_3=0 5x_D$ and while injection process is still in progress.

Expressions given in this part of paper make possible dynamic assigning of tactical ventilation and injection maneuvers for each of the cases described in table I The values calculated under these expressions are used in mathematical and computer modeling of ineruzation process.

4. MATHEMATICAL MODELING AND COMPUTER PROGRAM

Nitrogen distribution injected for volumetric inertisation into air flow follows convection diffusion mechanism, which is described by convection-turbulent diffusion equation:

$$\frac{\partial C}{\partial \tau} + u(s)\frac{\partial C}{\partial s} - D\frac{\partial^2 C}{\partial s^2} = \bar{q} \qquad (5)$$

with initial and boundary conditions.

$$\text{IC} \quad \left| C(s,0) = Co(s), \right.$$

$$\text{BC} \quad \left| C(0,\tau) = C_H(\tau); \ \frac{\partial C}{\partial \tau}\right|_{s=L} = 0$$

In equation (5) different expressions have the following meaning:

$\frac{\partial C}{\partial \tau}$ - transient in time; $u(s)\frac{\partial C}{\partial s}$ - convection transfer, $D\frac{\partial^2 C}{\partial s^2}$ - diffusion transfer, $\bar{q}(s,\tau)$ - gas source; s - coordinate in flow direction, $C(s,\tau)$ - transient in space and time concentration

In engineering practice concentration values are calculated by using simplified expressions obtained from equation (5) wlicn neglecting diffusion $(D\frac{\partial^2 C}{\partial x^2}=0)$ and mass inflow $(\bar{q}(s)=0, u(s)=\text{const})$ Solution of (5) with these simplifications give widely used in practice

Piston formulât'

$$C(s,\tau) = C_0 + (C_1 - C_0)\sigma_0(\tau - \frac{s}{u}), \quad \sigma_0(s - \frac{1}{u}) = \begin{cases} 0, \tau \le s/u \\ 1, \tau > s/u \end{cases}$$

and

Exponent expression

$$C(\tau) = C_0 e^{-A\tau} + C_H(1 - e^{-A\tau}); \quad A = \frac{u}{\Delta s}$$

The above formulas can't be applied in inertization prediction of real ventilation object because constant velocity is required That is why they can't be used for modeling of a gas source intrinsic for the panel and variable working cross-sections within.

In inertization tactics some of observed processes during injection, such as methane emissions and outflow of technical nitrogen from gob area, have steady-state character $(\frac{\partial C}{\partial \tau}=0)$. That is why they are modeled in presented study widi steady-state diffusion equation.

$$u(s)\frac{\partial C}{\partial s} - D\frac{\partial^2 C}{\partial s^2} = \bar{q} \qquad (6)$$

In general, modeling of inertization process is done on the full diffusion model (5). It has been solved numerically under Patankar/Spalding Control Volumes Method (Patankar,1980; Vlasseva,1988) The model deals with mixing of air environment with velocity u{s) and impurity q(s), i e. concentration C(S,T) can be obtained only of one gas component Inerting of real air media however as well as analysis of explosivity of formed air-gas mixture, presumes more than one gas impurities, namely:

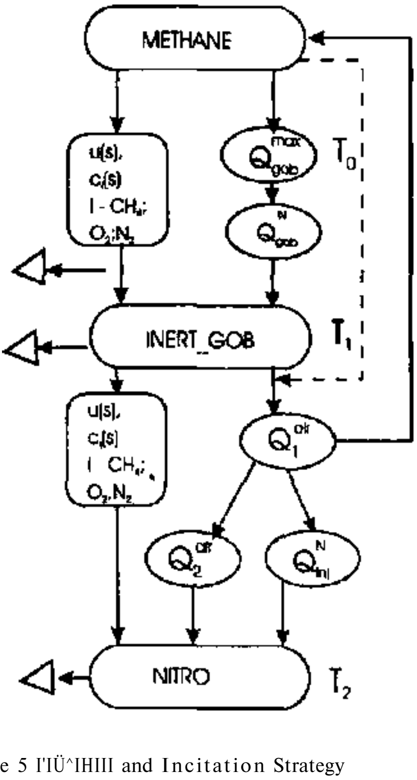
- methane inflow from gob area and from mine workings in the panel;
- oxygen from ventilation flow and from injected technical nitrogen;
- nitrogen from air and from injected technical nitrogen

Existence of other flamable gases cab be modeled also in case they play a role in explosivity of air-gas mixture.

In order to evaluate conceit I ration of the above mentioned three gas components via a model constructed foi ;i single component, the authors have applied consecutive diffusion mixing II pressumes appropriate defining of transporting medium and impurity as well as suitable presentation of gas souices q(s,Tj Table 2 presents the three calculation^ stages (methane release and distribution, nitiogcii outflow from gob aiea, nitrogen injection at a given place in the panel and its further distribution in the area which must be inert) For any of these singes computer modulus was developed - METHANE, INI.RT GOB and NI'IRO Common input data for the three computer programs are geometric characteristics of mine woikings (fig *İ)* The thiiT programs interact and the» memporatwg m the lokil niveitiiig sualcgy makes it possible the composition of general program procedure INERTIZATION Figure 5 presents consequence in usage and interaction of different modulae thus presenting the whole program and mretization strategy.

Table 2. Three Calculation Stages

Modulus name	Mathematical model	Transport media	Impurity	Gas source	Input data	Results
METHANE	steady -state diffusion (expr 5)	air	methane	along lenghths $\frac{q(s)}{L} = c$ from gob $\frac{q_{gob}(s)}{l_{2\text{-}3}} = var$	Qin, $C_{CH4}(0,0)$, $C_{O2}(0,0)$-, q_{CH4}-	$u(s), C_{CH4}(s)$, $C_{O2}(s); C_{N2}(s)$
INERT GOB	steady -state diffusion (expr 5)	air methane mixture	technical nitrogen from gob	$\frac{q_{GOB}(s)}{l_{2\text{-}3}} = var$	Results from METHANE + Q_{GOB}- ($\leq Q^{MAX}_{GOB}$ from(1)	$u(s), C_{CH4}(s)$, $C_{O2}(s); C_{N2}(s)$
NITRO	unsteady-state diffusion (expr 6)	air methane mixture + technical nitrogen from gob	injected technical nitrogen	fixed in space source (place of inj -table 1)	results from INERT_GOB + s_i, Q_{inject}	τ- time for inertization+ $u(s,\tau), C_{CH4}(s,\tau)$, $C_{O2}(s,\tau), C_{N2}(s,\tau)$



'igure 5 I'IÜ^IHIII and Incitation Strategy

5 MODELING OF TACTICAL SOLUTIONS

The program has been tested for all featured cases *for* panel (Figure 3) jnertization When crosscut working is not presented yet, in input data $L_{,,M} = 0$ is given Calculations follow the stages described on Figure 5 As a rule the next procedure uses velocity and concentrations fields from the previous one Values wntten in ellipses are the ones defined under expressions 1-4 Location of obtained results for atmosphere after each procedure can be observed in lespecl of explosion hazard zone (>) on figure 4 Feasibility of presented method and computer program is demonstrated on the following tactical example

> stage CI (Tabic 1)~ in gob area (5-6))- development of M'ONCOM is activated On treating u with nitrogen with maxima! volume *(Q^{N}_{ir}* 28m' /mm) required delay m its development is nol achieved The atmosphere ;ıl the most mky point in ihc pitnd is in [HJMIJOII In (I jyiite *A)*

4> isolation is undertaken with limited nitrogen icservts <md nsk of explosion An volume needed foi ventiUlion of (he pane! ıs ıeduced fıom *(J''''* 400 in /mm to *0''''* 110 m'/min leading to reduction of .in ltmv in coal 1ÎIU(?-3) huni ÎV) in /mm I<» ^{1}>7 nil/nun At a dist.nue of 200m lioiii ventilation en tidiuc (point I on I iguie i) ııılıoguı with *(.) [*, V/in' /nun i • n i ICI. lu! InHowmg subsUlultuii condition (3) and keeping nitrogen injection in gob

Q eob

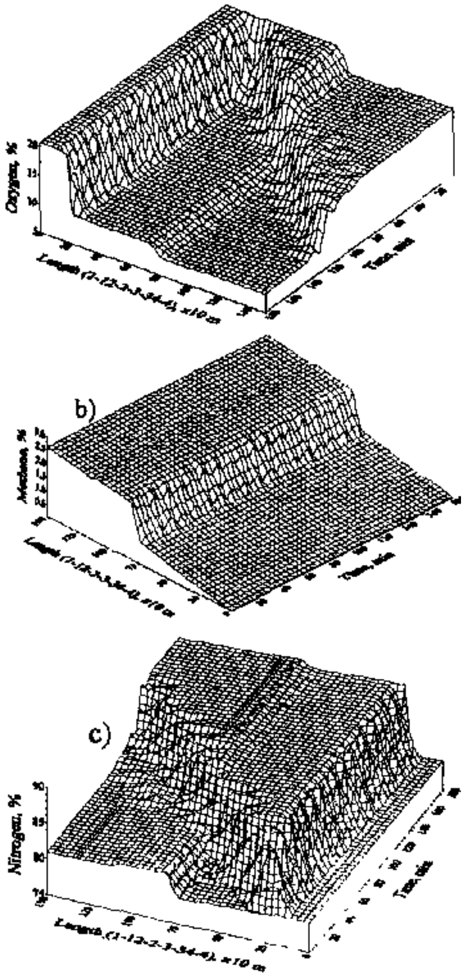


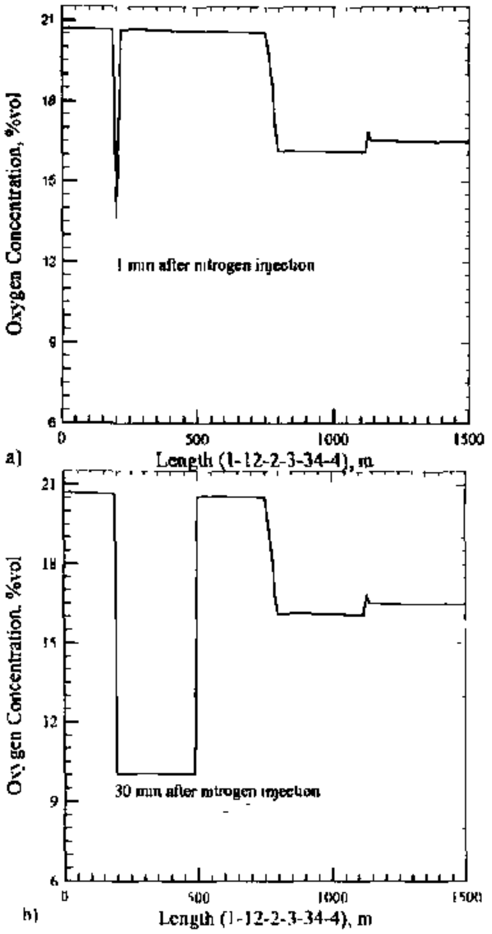
Figure 6 Variation in Oxygen, Methane and Nitrogen Content

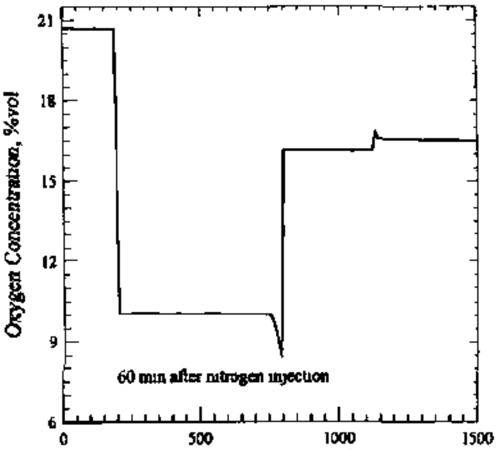
Figure 6 shows variations in oxygen, methane and nitrogen content during the period of mertization - 3 hours on route 1-12-2-3-34-4 (Figure 3). Figure 7 presents cross-sections in time of oxygen concentration for the example described above

6 DISCUSSION

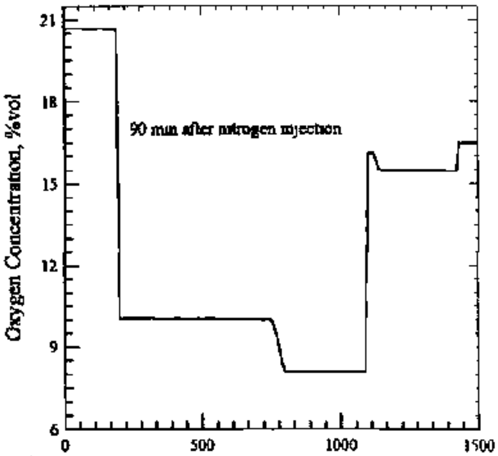
Tests with procedure presented here for consecutive diffusion mixing, including described example, clearly show its applicability for modeling of inertization of panel with real parameters The most important feature of computer program INERTIZATION is that it provides for analysis changes in gas picture in time and in panel space. Multi-variant modeling and analysis in risk fire situations during operative activities as well as in aspect of prediction can be made using the program.

Detailed information about dynamics of gas situation in time and space accompanies a wide range of tactically important data. These data for the example presented in the paper can be summarized as follows. For the total injection time 11 900 Nm^3 are injected in the panel. Oxygen concentration is reduced by 8% inertizing volume of 13512m^3 for three hours. At the end of inerting period only 1/9 part of injected' nitrogen is in the panel

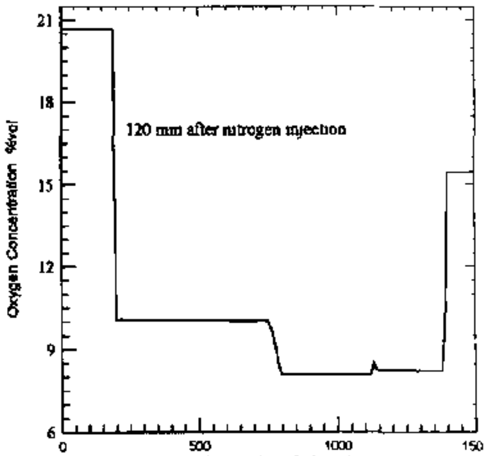



60 min after nitrogen injection
Oxygen Concentration, %vol
21
18
15
12
9
6
0
500
1000
1500
Length (1-12-2-3-34-4), m

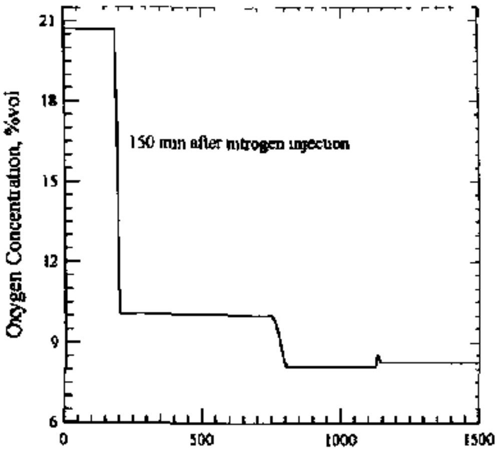
c)


90 min after nitrogen injection
Oxygen Concentration, %vol
21
18
15
12
9
6
0
500
1000
1500
Length (1-12-2-3-34-4), m

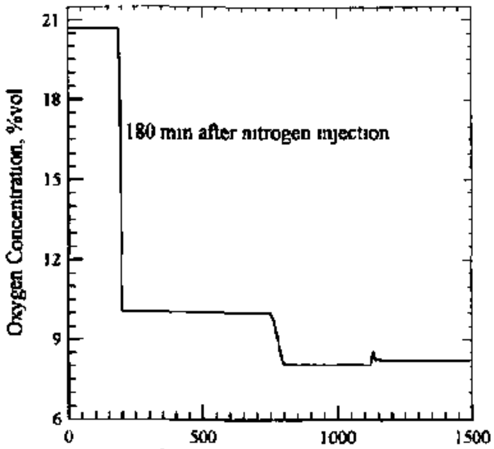
d)


120 min after nitrogen injection
Oxygen Concentration %vol
21
18
15
12
9
6
0
500
1000
150
Length (1-12-2-3-34-4), m

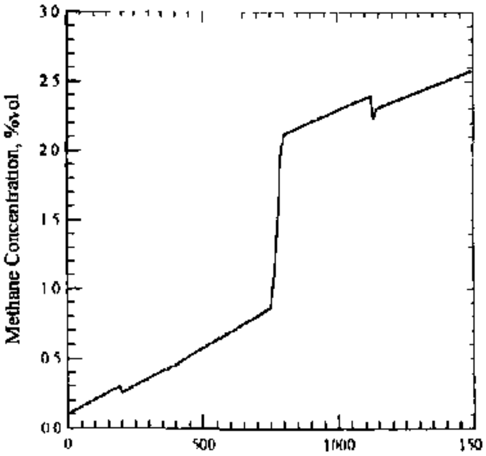
e)


150 min after nitrogen injection
Oxygen Concentration, %vol
21
18
15
12
9
6
0
500
1000
1500
Length (1-12-2-3-34-4), m

f)


180 min after nitrogen injection
Oxygen Concentration, %vol
21
18
15
12
9
6
0
500
1000
1500
Length (1-12-2-3-34-4), m

g)


Methane Concentration, %vol
3.0
2.5
2.0
1.5
1.0
0.5
0.0
0
500
1000
150
Length (1-12-2-3-34-4), m

h)

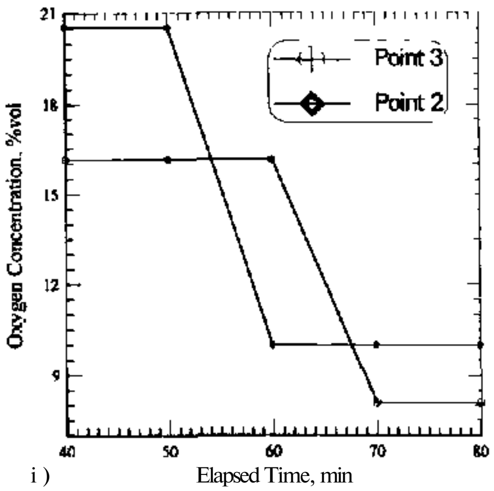


Figure 7. Cross-Sections in Time of Oxygen Concentration for the Example

Essential conclusion from modeling of methane distribution in gob area (Michaylov, 1996) and from analysis of mixing dynamics, made by here presented methodology and computer procedures, is that' during isolation or fire district nitrogen injection into gob area shouldn't be reduced of canceled.

Inertization periods evaluated with variation modeling are relatively short which is in accordance with practically proven observations during inertisation in mines. This can mean that when nitrogen quantities are enough, the dangerous operations on building and/or closing ventilation hatches in sealed stopping at return flow should be avoided before panel inertization starts Our opinion is that such risky operation (building stoppings or closing hatches) should start only when inertization is finished. Then, together with more favorable microclimatic conditions in the place of slopping building, risk of explosion is reduced maximally.

7 CONCLUSION

Ci i eat amounts of nitrogen needed for target and volumetric inertization in mines require grounds for flow rates effective from technical and tactical point of view nitrogen. Preliminary analysis of different tactical solutions for nitrogen injection can make these costs optimal via choosing of safety tactics of ventilation maneuvers and of the process of injection into fire section

hffcen years practice in anti-fire mciti/ation of tire striions in Bulgaiia leads tow.mis ist-ul of pn-diclivi' modeling and, as close as possible, to real operative calculations of inertization dynamics. Procedure for consecutive diffusion mixing, presented in this paper, and its computer realization - program INERTIZATION provides possibility for dynamic modeling and analysis of volumetric inertization of fire sections with their real physical parameters

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